CP violation in top-quark pair production and decay

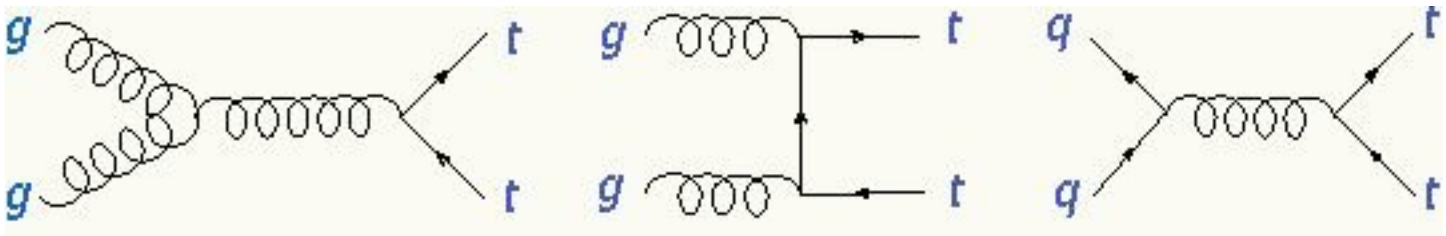
Using T-odd correlations to search for CP violation from new physics in top-quark pair production and decay at the LHC

- *based on work with
  - Sudhir Kumar Gupta (ISU postdoc, now Monash)
  - Oleg Antipin (ISU student, now CP^3 Origins postdoc)
  - Sehwook Lee (DØ ISU student, DØ thesis)
  - Xiao-Gang He and Hiroshi Yokoya (NTU)

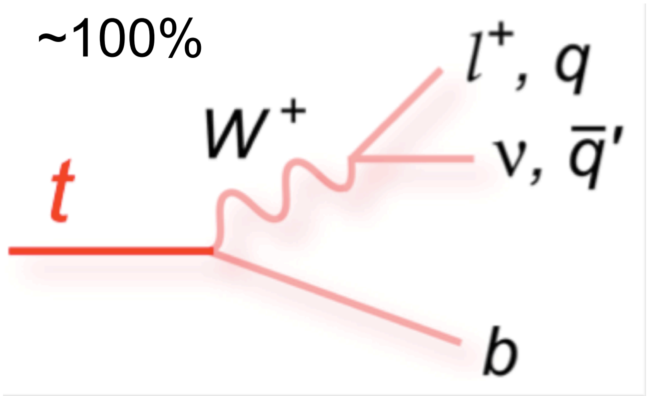
G. Valencia (Iowa State), ICHEP Melbourne 2012

Top-pair production at LHC

- The LHC is turning into a top-quark factory, opening up an era of precision measurements of top-quark properties.
- One important aspect of this program should be the search for CP violation (top cedm?)
- at LHC top-pair production occurs mostly through gluon fusion



- and decay within the SM follows:



T-odd correlations

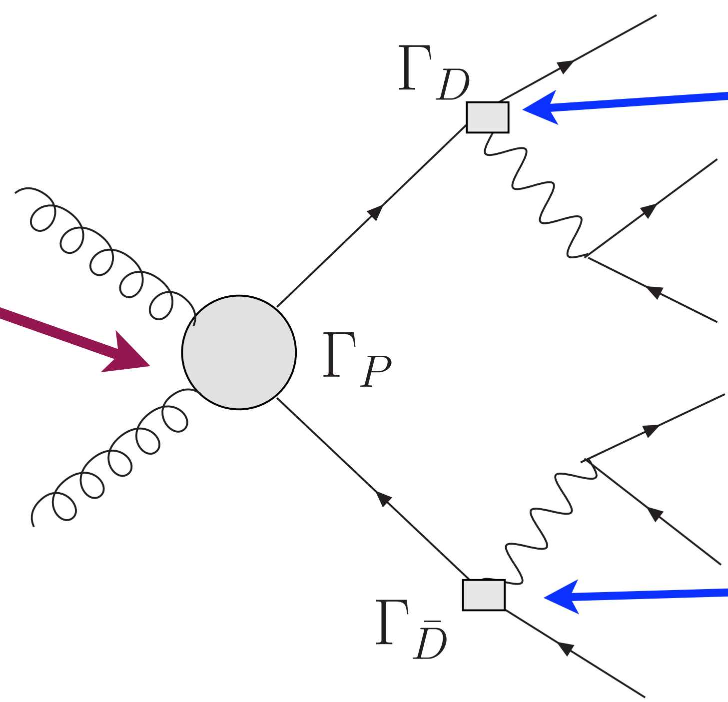
- For this configuration, CP violation would manifest itself via certain spin correlations that give rise to CP-odd triple product correlations involving lepton, jet and beam momenta.
- T-odd correlations change sign under `naive'-T (without interchange of initial/final states) so not always CP-odd
  - CP-odd if they involve particle anti-particle pairs (or sums over them)
  - CP-even but not at tree-level as they require a phase -- small and distinguishable `background'
- The momenta in the correlation can be that of a composite object (jet) reflecting observables that sum over processes
- Within the SM CP violation in top-pair production/decay is extremely small, insuring that any observation would signal new physics.

New physics and CP violation

- the underlying T-odd correlations are spin correlations, different observables correspond to different spin analyzers

$\epsilon(p_t, p_{\bar{t}}, s_t, s_{\bar{t}})$

CP violation in the production vertex



$\epsilon(p_t, p_b, p_{\ell^+}, s_t)$

CP violation in the decay vertex

$\epsilon(p_{\bar{t}}, p_{\bar{b}}, p_{\ell^-}, s_{\bar{t}})$

- covariant form of triple products

$$\epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-}) \equiv \epsilon_{\mu\nu\alpha\beta} p_t^{\mu} p_{\bar{t}}^{\nu} p_{\ell^+}^{\alpha} p_{\ell^-}^{\beta}$$

CP odd triple-products

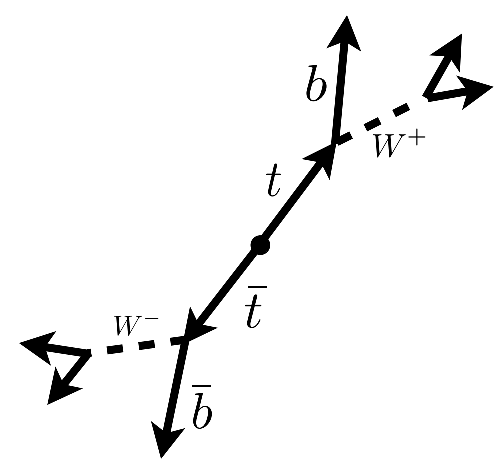
- Start from a T-odd correlation such as

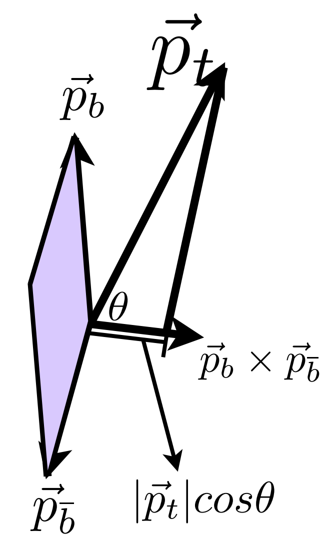
$$\mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) \xrightarrow{(t\bar{t})_{\rm cm}} \propto \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$

$$\xrightarrow{CP} -\vec{p}_{\bar{t}} \cdot (-\vec{p}_{\bar{b}} \times -\vec{p}_b) = -\vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$

- measure odd terms in the dσ/d$\mathcal{O}_1$ or an integrated counting asymmetry: In top pair center of mass for example:

$$A_{CP} \equiv \frac{N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) - N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)}{N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) + N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)}$$





- Within the SM these CP violating observables are nearly zero, insuring that any observation would signal new physics.

Some possible correlations

di-lepton channel, CP violation:

$$\tilde{\mathcal{O}}_{1\ell\ell} = \epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) \xrightarrow{b\bar{b}\ CM} \propto \ \vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$$

$$\tilde{\mathcal{O}}_{2\ell\ell} = \tilde{q} \cdot (p_{\mu^+} - p_{\mu^-})\, \epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})$$

T-odd but CP even `unitarity' phase:

$$\mathcal{O}_{a\ell\ell} = \tilde{q} \cdot (p_{\mu^+} + p_{\mu^-})\, \epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})$$

quadratic in beam direction, $\tilde{q}$

lepton plus jets channel, CP violation (2) and T-odd phase (a):

$$\mathcal{O}_{2\ell j} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto \ (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$\mathcal{O}_{a\ell j} = \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto \ (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

hadronic channel, CP violation:

$$\mathcal{O}_{5jj} = \epsilon(p_b, p_{\bar{b}}, p_{j1}, p_{j1'}) \xrightarrow{b\bar{b}\ CM} \propto \ \vec{p}_b \cdot (\vec{p}_{j1} \times \vec{p}_{j1'})$$

$$\mathcal{O}_{6jj} = \epsilon(p_b, p_{\bar{b}}, p_{j1} + p_{j2}, p_{j1'} + p_{j2'}) \xrightarrow{t\bar{t}\ CM} \propto \ (\vec{p}_{j1} + \vec{p}_{j2}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$

- Not always necessary to distinguish b from $\bar{\mathrm{b}}$,
- non-b jets can be ordered in any CP blind way, e.g. by p_T
- j1, j1' can be defined, e.g. as closest to b and b' (no need for further id)

Examples of new CP violating physics

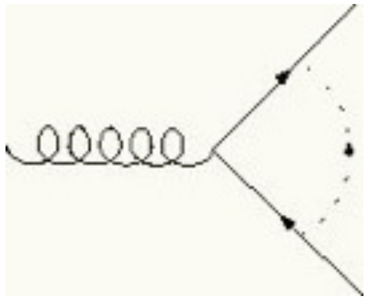
- Anomalous top-quark couplings
  - exhibit the correlations in the general case (including those between initial and final state momenta)
  - contains examples that are truly CP odd and others that are not (due to unitarity phases)
  - small asymmetries (anomalous couplings are small by assumption)
- Extended scalar sectors with CP violation
  - large intrinsic asymmetry possible ~ 13%
  - hard to extract
  - only one correlation (can't involve beam momentum)

quark edm (cedm)

- edms indicate T violation (and thus CP violation)

edm $\quad \mathcal{H} \sim \frac{1}{2}\, e\, d_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 q\, F^{\mu\nu} + \frac{1}{2}\, g_s\, \tilde{d}_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 t_a q\, G_a^{\mu\nu} \quad$ cedm

- experimental limits on electron edm and neutron edm; for example $d_n < 2.9 \times 10^{-26}$ e-cm
- for example models with scalars generate contributions such as

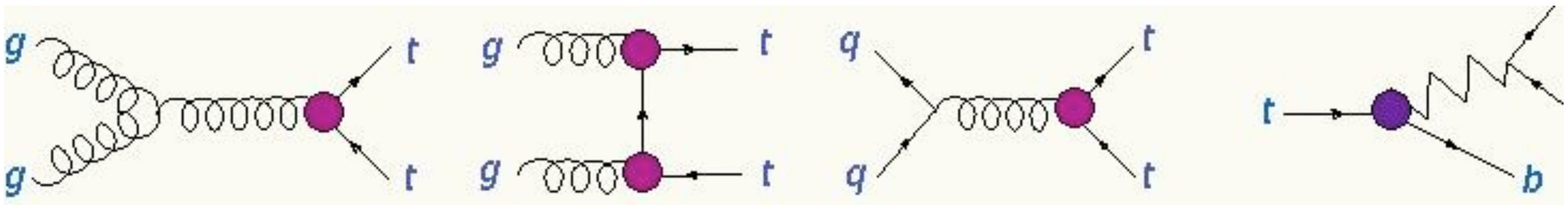


$$d_q, \tilde{d}_q \sim m_q^3$$

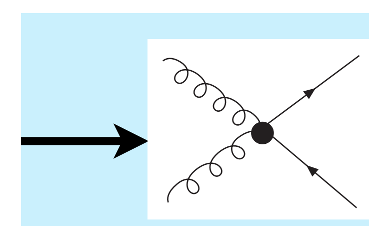
- speculate these can be large for heavy fermions
- perhaps heavy quarks (top) can have large (c)edm

CP violating anomalous couplings

- Anomalous couplings



- Ones that produce CP-odd correlations in the m_b=0 limit:
  - top quark cedm $\mathcal{H} \sim \frac{1}{2} g_s \tilde{d}_t \, \bar{t} \sigma_{\mu\nu} \gamma_5 \lambda_a t \, G_a^{\mu\nu}$



  - t-b W: $\mathcal{H} \sim i \frac{g}{\sqrt{2}} V_{tb}^{\star} f_2^R \, \bar{b} \sigma^{\mu\nu} (p_t - p_b)_\nu (1 + \gamma_5) t \, W_\mu$

- Constraints on these CP-odd observables (or observation) can be translated into bounds on the (chromo)-electric-dipole moment (cedm) of the top-quark and/or f_2^R.

Event generation

- We use MadGraph for all signal and background events (FeynRules and `by hand') - several checks were made using analytic results
- There are no background issues beyond those for top-pair selection
  - Known backgrounds: $QCD,\ Vb\bar{b},\ Vc\bar{c},\ VV,\ (V=W^{\pm},Z)\cdots$ are CP symmetric (in SM) and with CP-blind cuts cannot mimic the signal
  - use some `typical' selection cuts for our analysis. For example for dimuons, the cuts

$$p_T(\mu^{\pm}) > 20\text{ GeV} \quad p_T(b,\bar{b}) > 25\text{ GeV} \quad \not{E}_T > 30\text{ GeV}.$$
$$|\eta(b,\bar{b},\mu^{\pm})| < 2.5 \quad \Delta R(b\bar{b}) > 0.4.$$

  - reduce (S,B) from (4.3 pb, 24 pb) to (2.6 pb, 1.2 pb) and (2.3 pb, 0) respectively
  - residual background simply dilutes the statistical sensitivity by factors

$$\sqrt{(B+S)/S}$$

- Find 5 σ (stat) sensitivity to 3% asymmetries per 10 fb^{-1} at 14 TeV

Asymmetries translate into bounds on anomalous couplings

coupling	top cedm $\tilde{d}\ \left[\frac{1}{m_t}\right]$	$t \to b$ decay $f\ \left[\frac{1}{m_t}\right]$
Sample theory Estimates	$<10^{-13}$ SM* $\sim10^{-6}$ H^{+}* $\sim10^{-3}$ SUSY* ~0.003 (v.l multiplets)**	0.03 QCD& CP conserving, no phases. Phases occur at next order (with extra gluons)$
LHC with $10fb^{-1}$ at 14 TeV 5 σ sensitivity	0.05	~ 0.10 (both CP and/or strong phases)

units → $3.0 \times 10^{-4}\ \mathrm{GeV}^{-1} \leftrightarrow \frac{0.05}{m_t} \leftrightarrow 5 \times 10^{-18} g_s \cdot \mathrm{cm}$

* David Atwood et. al. **CP violation in top physics, Phys.Rept.347:1-222,20001.**

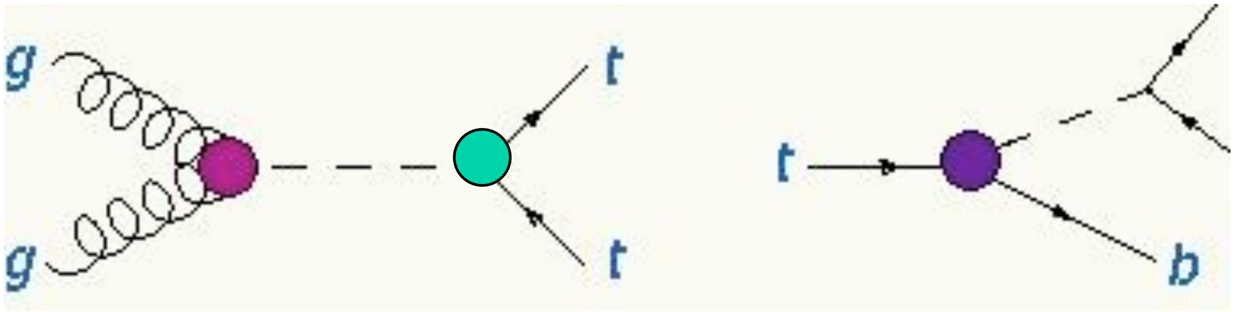
& Chong Sheng Li, Robert J. Oakes, Tzu Chiang Yuan **Phys.Rev.D43:3759-3762,1991**.

** Ibrahim, Nath PRD84 (2011) 015003

$Hagiwara K., Mawatari K. and Yokoya H., *JHEP*, **0712** (2007) 041

CP violation in new Resonances

- Only possibility to get a CP odd correlation in the m_b=0 limit, without new heavy fermions is a scalar resonance:



- In production it can be a color singlet or octet
- In decay doesn't work as easily so ignore for now

color octet scalars

- Scalar sector of SM extended with a color-octet electroweak-doublet (motivated by MFV)
- Yukawa sector

$$\mathcal{L} = -\frac{\sqrt{2}}{v}\eta_U\, e^{i\alpha_U}\, \bar{U}_R T^A \hat{M}^u U_L\, S^{A0} + \text{ h.c.} + \cdots$$

new CP phases

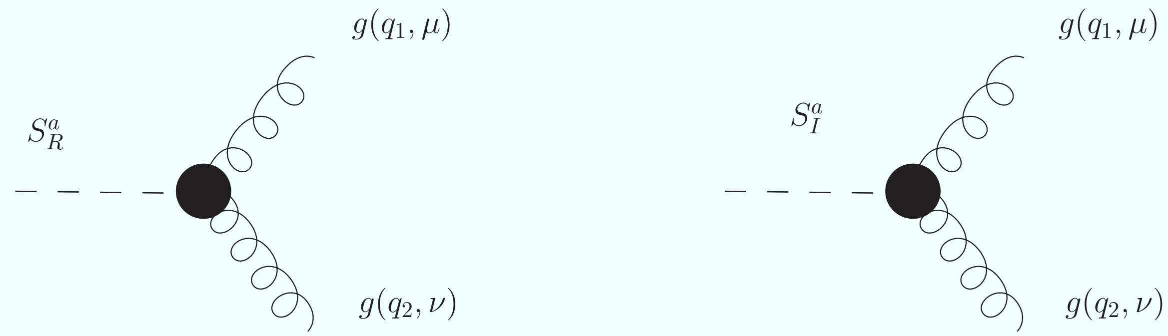
- Scalar potential

$$V = \frac{\lambda}{4}\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_s^2 \mathrm{Tr}\, S^{\dagger i}S_i + \lambda_1 H^{\dagger i}H_i \mathrm{Tr}\, S^{\dagger j}S_j + \lambda_2 H^{\dagger i}H_j \mathrm{Tr}\, S^{\dagger j}S_i$$
$$+ \left[\lambda_3 e^{i\alpha_3} H^{\dagger i}H^{\dagger j}\mathrm{Tr}\, S_i S_j + \lambda_4 e^{i\alpha_4} H^{\dagger i}\mathrm{Tr}\, S^{\dagger j}S_j S_i + \lambda_5 e^{i\alpha_5} H^{\dagger i}\mathrm{Tr}\, S^{\dagger j}S_i S_j + h.c\right] + \lambda_6 \mathrm{Tr}\, S^{\dagger i}S_i S^{\dagger j}S_j + \cdots$$

  - α_3 can be chosen to be 0
  - custodial symmetry requires $\alpha_4 = -\alpha_5$

CP violating couplings

$$i\ (a_{R,I} + i b_{R,I}\ \gamma_5)\ T^A$$

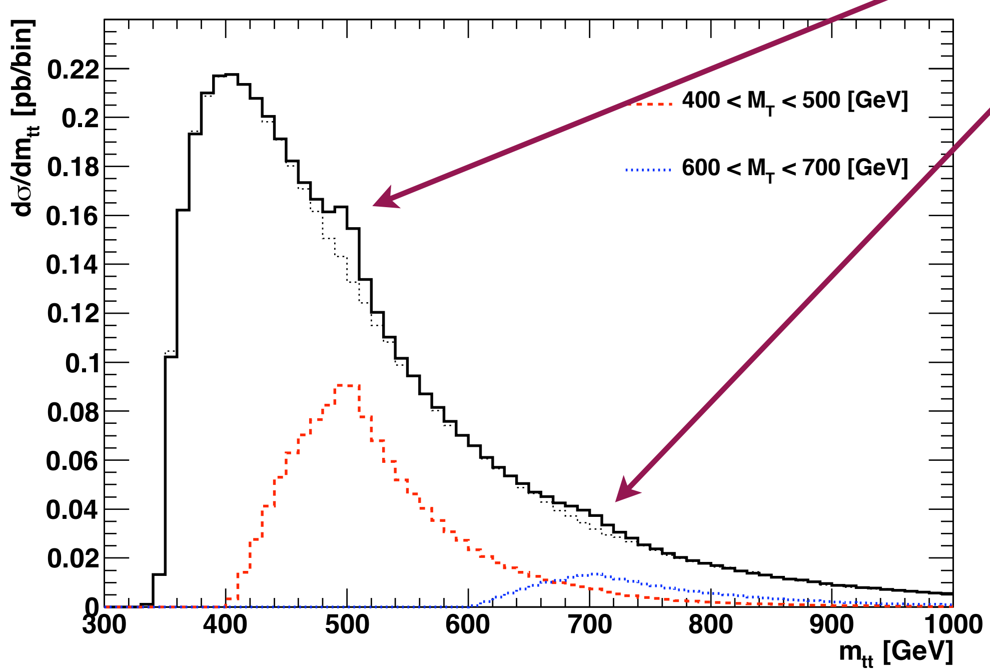


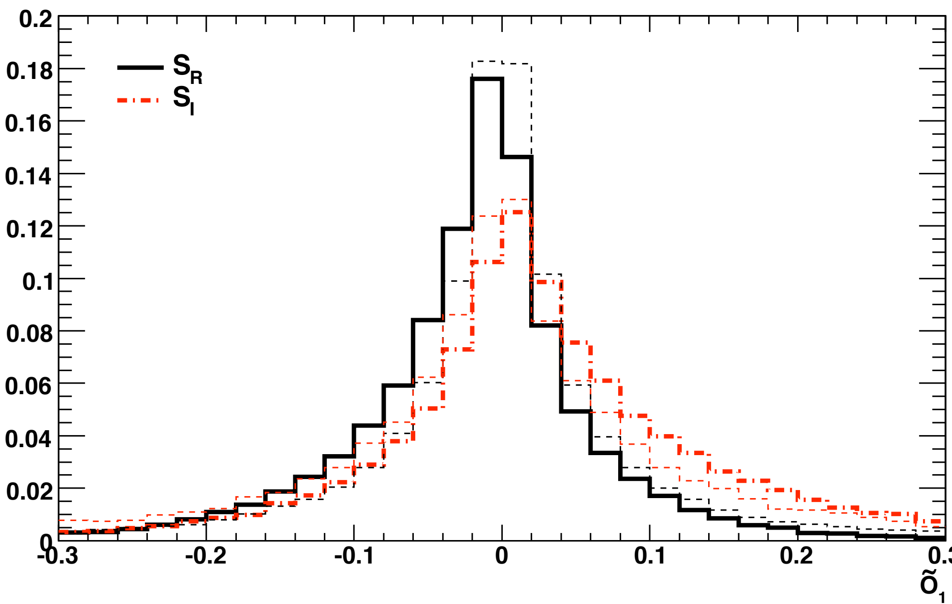
$$4\ i\ \left(F^a_{R,I}\ (q_{2\mu} q_{1\nu} - q_1 \cdot q_2\ g_{\mu\nu}) + F^b_{R,I}\ \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right)\ d^{ABC}$$

CP violation shows up as mixing of scalar and pseudo-scalar components in the scalar mass eigenstates.

color-octet, neutral scalars

- parameters chosen so that the resonance `stands out' (minimally here)





- asymmetry without QCD background: the two resonances induce opposite sign asymmetries

FIG. 4: $d\sigma/dm_{t\bar{t}}$ distributions without and with contribution of scalars in Case $1'$, plotted in dotted and solid line, respectively, in an unit of pb per 5 GeV bin. Dashed lines are for the distribution after $400 < M_T < 500$ [GeV] (red long-dashed) and $600 < M_T < 700$ [GeV] (blue short-dashed) cuts.

color octet raw asymmetries

$$\tilde{\mathcal{O}}_1 = \epsilon_{\mu\nu\alpha\beta}\, p_b^\mu\, p_{\bar{b}}^\nu\, p_{\mu^+}^\alpha\, p_{\mu^-}^\beta \xrightarrow{b\bar{b}\ CM} \propto\ \vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}).$$

	Parameters	Decay Width [GeV]	Resonance cross-section [fb]	Raw asymmetry around resonance
Case 1′	$m_R, m_I = 500, 700$ GeV, $\eta_U = 3, \lambda_{4,5} = 1,\ \alpha_u = \pi/4$	S_R : 24.3 S_I : 47.7	S_R : 60.4 S_I : 24.0	S_R : $A_1 = -0.127$ S_I : $A_1 = 0.103$
Case 2′	$m_R, m_I = 500, 700$ GeV, $\eta_U = 3, \lambda_{4,5} = 8,\ \alpha_{u,4} = -\alpha_5 = \pi/4$	S_R : 24.3 S_I : 47.7	S_R : 43.2 S_I : 24.2	S_R : $A_1 = -0.122$ S_I : $A_1 = 0.129$
Case 3′	$m_R, m_I = 500, 700$ GeV, $\eta_U = 3, \lambda_{4,5} = 1,\ \alpha_u = \pi/8$	S_R : 18.8 S_I : 52.5	S_R : 75.8 S_I : 26.9	S_R : $A_1 = -0.117$ S_I : $A_1 = 0.076$

TABLE II: Parameter values, resonance $S_{I,R}$ decay-widths and production cross-sections $\sigma(pp \to S_{I,R} \to t\bar{t} \to b\bar{b}\mu^+\mu^-\nu\bar{\nu})$ at the LHC $\sqrt{S} = 14$ TeV, and raw CP asymmetry for the five cases discussed in the text with $\eta_U = 3$. The raw asymmetry is defined by taking into account the events with $|m_{t\bar{t}} - m_{I,R}| < 10$ GeV.

	Asymmetry around resonance including SM amplitudes	Integrated asymmetry including SM amplitudes	M_T cut
Case 1′	S_R : $A_1 = -0.017(2)$ S_I : $A_1 = 0.029(4)$	$A_1 = 0.0002(5)$	Low : $A_1 = -0.0045(10)$ High : $A_1 = 0.0141(23)$

Recent D0 measurement

- Sehwook Lee D0 PhD Thesis:

  "CP violating anomalous top-quark coupling in ppbar collision at √s = 1.96 TeV", 2011

- Best result in lepton plus jets channel with

$$\mathcal{O}_2 \quad = \epsilon(P, p_b + p_{\bar{b}}, p_l, p_{j_1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_l \times \vec{p}_{j1})$$

	$A_{central}$	$\sigma_{stat.}$	$\sigma_{dilution}$	$\sigma_{sys.}$	$\sigma_{stat.+dilution+sys.}$
O_2	+0.106	$^{+0.080}_{-0.081}$	$^{+0.035}_{-0.039}$	$^{+0.014}_{-0.017}$	$^{+0.088}_{-0.091}$

- statistical errors dominate, systematics under control at this level...

Conclusions

- The top physics program at LHC presents a unique opportunity to search for new sources of CP violation through simple kinematic correlations.
- For example, with 10 fb^{-1} at 14 TeV, the LHC would have a 5 σ statistical sensitivity to the top cedm of 0.05 in units of m_t^{-1}. This is about an order of magnitude away from some (new physics) model predictions.
- CP violating intrinsic asymmetries as large as 13% are possible in models with new scalar/pseudo-scalar resonances.
- Observation of these asymmetries requires, however, identification of the new resonance above the QCD `background'.
- There already exists a D0 thesis measuring these observables. We urge ATLAS and CMS to carry out these measurements.